CONCRETE HIGHWAY PAVEMENTS IN AUSTRALIA

GP Ayton

Roads and Traffic Authority, New South Wales
Australia

ABSTRACT

Since 1975, the Roads and Traffic Authority (RTA) has promoted the increased use of concrete pavements throughout the state of New South Wales (NSW). In the period up to mid-1993, approximately 1300 lane-km of concrete pavement have been constructed.

The Australian industry expanded rapidly in an environment which is geographically remote from overseas areas of long-standing experience such as the USA and Western Europe. The adoption of this relatively new technology in the Australian context attracted close attention from both the media and the travelling public. Neither group is tolerant of difficulties associated with the "learning curve" process and it has therefore been a major priority to implement and refine good design and construction practices as rapidly as possible.

Current Australian practice reflects a blending of local experience with that from leading overseas authorities.(17)

This paper summarises local developments in Australian concrete pavement technology since the mid 1970's and discusses the major lessons learnt from both the achievements and the problems encountered along the way.

Recent indications point to a likely growth in concrete pavement construction throughout the South East Asian region and recent Australian experience would appear to be relevant.

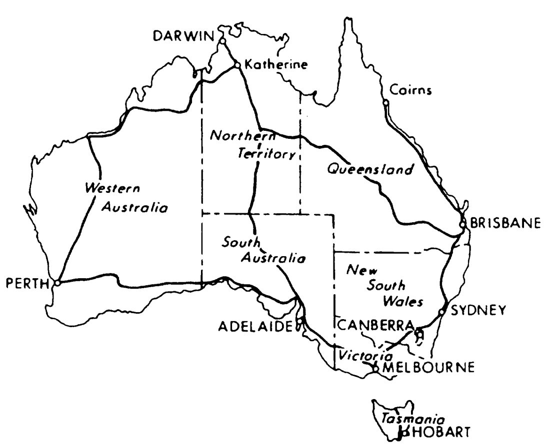


Fig 1. The Australian national highway system

GEOGRAPHIC

Australia has a land area of approximately 7.68 million sq km which is about 90% of that of continental USA. Of a total population of 18 million, about 9 million live in the south east corner within the Sydney-Melbourne corridor in an area approximately the size of the state of Texas.

The state of New South Wales has a total land area of about 800,000 sq km which is about 15% larger than Texas.

The topography of the eastern states is of low relief with two thirds of NSW having an elevation less than 300 m. The coastal strip contains substantial areas of alluvial swamp broken by coastal rivers, and this is backed by the Great Dividing Range with peaks generally at about 1500 m but to a maximum of 2230 m a short distance from the east coast at Mt Kosciusko.

Fig. 2 illustrates the length of road per head of population for a number of countries. The comparison provides an indication of Australia's difficulties in providing a road network to meet the high expectations of a population with a penchant for long distance travel.

The task of maintaining the network is made all the more difficult by the fact that approximately 70% of all freight is carried by road, compared with only 20% by rail.(18)

In the eastern areas of Australia where concrete pavements are most commonly constructed, the typical seasonal temperature range is -5°C to 40°C (25°F to 105°F). None of the major arterial highways is subjected to significant subgrade freezing.

Average annual rainfall within this area varies between 400 and 2400 mm (15 to 95 in.).

The main effects of the topography and climatic conditions are their influence on subgrade moisture conditions and the seasonal and diurnal effects on asphaltic wearing surfaces.

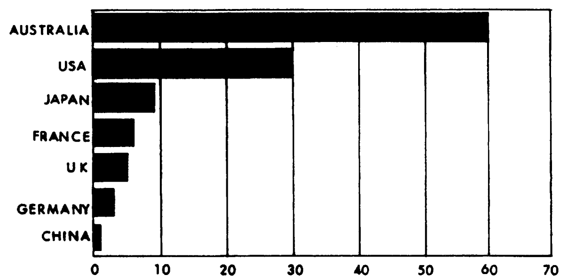


Fig 2. Length of road (metres) per head of population

EARLY CONSTRUCTION IN AUSTRALIA

Concrete pavements were constructed in Australia as early as 1880 when the Sydney City Council began a program of reconstructing its most heavily trafficked downtown streets with 150 mm of concrete.

It was a surprise to the author to find that this was some 11 years earlier than the first recorded use of concrete pavements in the USA in Bellefontaine, Ohio (1).

In those areas of Sydney where "*... the weighty, iron-shod traffic from the wharves and warehouses concentrates*" the council placed a surfacing of wooden blocks over the concrete. In a process termed "*cement penetration*", it is reported that "*... the water was slopped on, as was the way a very long time after 1880.*"

It is recorded in Sydney's journals of 1931 (2) that "*... the concrete is still giving its hundred percent of service after fifty years.*" Nevertheless, in 1918 a new design was adopted comprising 230 mm of "*unsurfaced cement concrete*". This change was motivated by the desire to "*... eliminate the terrific maintenance problem inseparable from other construction*".

It is interesting to note that this claimed justification for concrete pavements has changed little in the past 75 years.

In 1934 it was recorded (3) that a process termed "*Roller Compressed Concrete*" was now well established in Sydney after successful trials in New Zealand and Melbourne (Australia). Further, on heavily trafficked routes in Sydney, "*... it has been the policy of the City Council to use a rapidly hardening cement in the construction of highways. The extra cost, it is contended, is justified by the saving in inconvenience to roadusers*".

Sydney City's almost total reliance on roller compacted concrete continued until 1992, when the batching plant was demolished because of the high value of the real estate which it occupied. It had proven to be an ideal material for metropolitan construction and it appears unlikely that an equivalent material will be found.

The Main Roads Board of New South Wales also constructed substantial lengths of concrete pavement in the 1920s and 1930s, in both urban and rural areas.

Many of the so-called "depression roads" built in that period are still in use, largely within Sydney and Melbourne and on the Pacific Highway on the north coast of New South Wales. A further active period of construction occurred in the 1950's and early 1960's but little was completed thereafter until 1975.

The older concrete pavements typically now have poor ride quality and a high maintenance demand at the transverse joints. These pavements were constructed with designs and by methods which would be unacceptable by today's standards. In particular, the absence of effective subbases is entirely unsuitable for modern heavy traffic loads.

Despite this retrospective criticism, most have provided service well beyond their design life under traffic loadings far more severe than were ever anticipated.(11) In general, however, they are unfavourably regarded by a large proportion of Australian drivers because of the poor ride quality resulting from uneven settlement and joint stepping.

Over the past decade, New South Wales has completed the construction of more than 1300 lane-km of concrete pavement incorporating designs and methods which had not previously been seen in Australia. The success of these developments is indicated by the fact that motorists using these new roads are now often unaware that they are travelling on concrete.

CONCRETE PAVEMENTS IN THE 1980'S

During the 1980's, the RTA promoted a resurgence in the construction of concrete pavements throughout the state, and a high level of construction continues to this day. This can be sourced back to the construction in 1975 of the RTA's first continuously reinforced concrete pavement, and the success of that project prompted ongoing interest.(8)

Of the other Australian states, only Victoria is constructing significant lengths of concrete pavement. The remaining five states are blessed with more favourable combinations of local geology and traffic demands, and are therefore constructing flexible pavements almost exclusively.

The current direction in NSW reflects to some extent the growing confidence derived from the ongoing successful completion of a series of major projects, but also of significance are the following factors:

* NSW is rapidly exhausting its limited sources of high quality road aggregates suitable for the construction of flexible pavements.

* Specific routes within NSW are subjected to the heaviest intensity of truck traffic in Australia. Additionally, very poor subgrade conditions exist over substantial lengths of those routes.

* Australia's oil deposits lack the heavier fractions and therefore all bituminous products must be made from imported crude oil.

CONCRETE PAVEMENT INVENTORY

The length of concrete pavement constructed on inter-urban routes within NSW since 1975 is as follows:

▪ Continuously reinforced:	310 lane-km
▪ Plain (undowelled):	1000 lane-km
▪ Jointed reinforced:	10 lane-km
Total:	1320 lane-km

Additional to this inventory, substantial lengths have also been constructed on urban arterial routes throughout Sydney, through rural towns and city centres, on roundabouts in metropolitan and rural areas and in bus bays and transport interchanges.

PAVEMENT THICKNESS DESIGN

Road design guidance in Australia is set by the the Association of Australian State Road Authorities (AUSTROADS) in a role similar to that of AASHTO.

The AUSTROADS pavement thickness design method was substantially revised in 1991 to reflect developments in design models throughout North America, Europe and the United Kingdom during the second half of the 1980s. The current design method (4) is based on an Engineering Bulletin issued in 1984 by the Portland Cement Association (PCA) in the USA (5).

On the major arterial routes where concrete pavements are used, design traffic loadings are typically within the range of 5×10^7 to 1.5×10^8 Equivalent Standard Axles (ESA's).

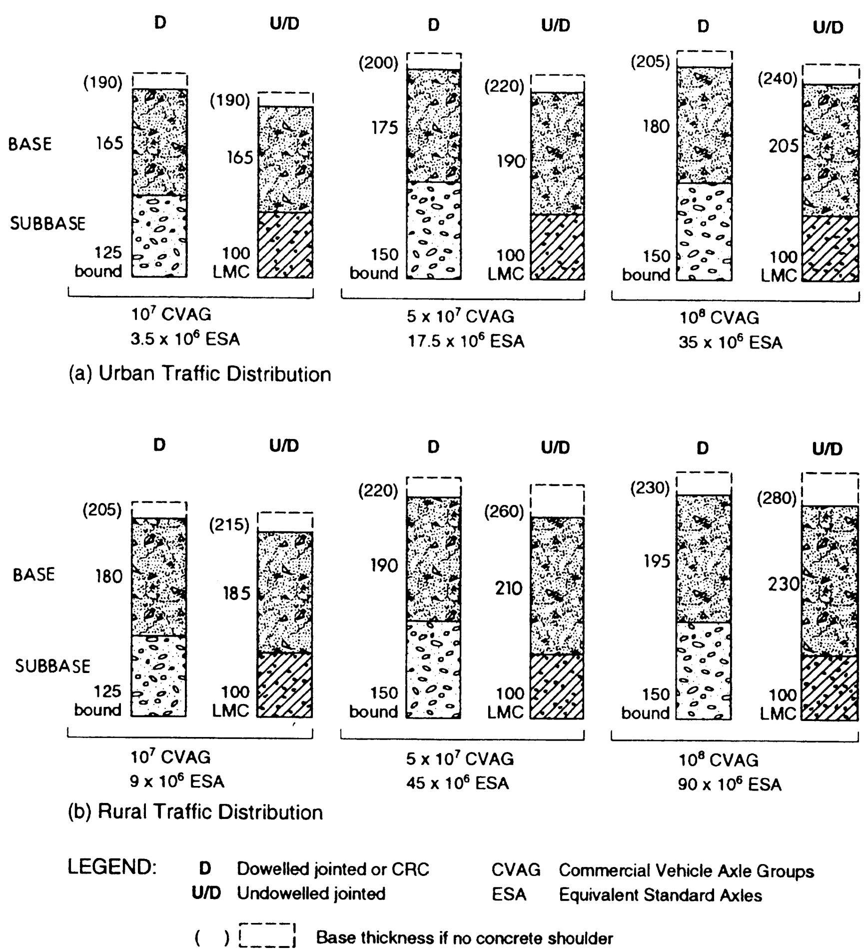
Maximum statutory axle loads throughout Australia are as follows:

* Single axle, dual tyres:	8.5t
* Dual axles, 8 tyres:	15.0t
* Three axles, 12 tyres:	18.0t

Typical rigid pavement thicknesses are shown in Fig 3. Note that in Australia the term "base" refers to the main concrete pavement layer.

A brief discussion on typical pavement configurations follows.

Fig 3. Typical AUSTROADS pavement designs(6)



SELECT SUBGRADE

In urban freeway and rural construction, a select subgrade layer of 300 mm of the best locally available embankment material will typically be placed in the upper portion of the subgrade. A minimum CBR of 15% is typically specified and this will often necessitate stabilisation by lime or cement. A bituminous sprayed seal will usually be applied to protect the surface both before and during the paving contract.

In urban construction other than on freeways, it will rarely be viable to provide a select subgrade layer and the design will therefore be based on the insitu saturated CBR which will typically be within the range of 2 to 5%. The prime consideration in preparing the subgrade under these conditions will therefore be the achievement of as uniform a support as possible within acceptable level tolerances.

SUBBASE

By far the majority of construction since 1975 has included a Lean-mix Concrete (or econocrete) Subbase (LCS). A concrete subbase of 100 mm is the minimum requirement under an undowelled jointed pavement, and is also recommended under dowelled and continuously reinforced pavements for the combination of subgrade and traffic loadings typically encountered on the highway network.

Rolled Lean Concrete (RLC) subbases have also been used but they have proven less attractive than conventional wet mixes because of the difficulty of achieving uniform and adequate compaction with rolled granular materials. For the same reason, they are no longer considered equivalent to conventional wet mixes. Additionally, the paving industry favours the use of wet mixes to enable fuller utilisation of their slipform pavers and mixing plants.

Lean-mix concrete subbases have proven economically competitive because of the extreme shortage of suitable naturally occurring gravels along the east coast and the ready availability of satisfactory flyash supplies, from coal-fired electric power stations.

The characteristics of the LCS are as follows:

* Minimum compressive strength: 5 MPa at 6 weeks. Acceptance is based on core strength rather than cylinder strength. For the laboratory trial mix, an upper limit of 15 MPa is specified.

* Maximum shrinkage of 550 microstrain.
  This is tested before construction commences and during validation of the contractor's proposed mix design. Close controls are thereafter specified on variations to the nominated mix.

* Cementitious contents:
  total cementitious: 250 kg/m^3 minimum
  portland cement: 70 kg/m^3 minimum
  flyash: 100 kg/m^3 minimum

  Blended cements incorporating flyash or slag are permitted. The mixes typically proposed by contractors comprise of 170-180 kg/m^3 of flyash and 70-80 kg/m^3 of cement. These high flyash mixes have proven to be well suited to slipforming. Additionally, their strength development characteristics give the preferred pattern of fine cracks at spacings of 5 to 15 m. The maximum permitted strength of 15 MPa at 28 days ensures that rejected base concrete from nearby projects is not diverted into the subbase.

* Air entrainment: optional, but encouraged at contents up to 7%, because of its beneficial effects on slipformability, reduction of water/cement ratio and suppression of bleeding. Because of the inherent variability in the carbon content of flyash, it is essential that the actual air content be continually monitored.

* Aggregates: quarried aggregates are normally used, but blast furnace slag aggregates are permitted. To date, recycled aggregates from old concrete have not been used.

The overall performance of lean-mix subbases has been very good, and to date there have been no signs of surface erosion. Investigations during slab replacement works indicate that the LCS provides an effective waterproofing (or at least water-shedding) layer which protects the subgrade from significant moisture variation. Any water which enters the pavement appears to flow on top of the subbase and is readily collected in pavement edge drains. At this stage, therefore, there appears to be no reason to follow the example of overseas authorities in trialling permeable subbases.

Since 1988, the acceptance criteria for concrete subbases have been based purely on core testing from the hardened subbase, and cylinders are not required. These criteria were introduced following repeated contract disagreement over the application of cylinder results, and it had become accepted practice to resort to core testing to resolve the dispute.

Under current specifications, the insitu strength (after wet conditioning of between 1 and 3 days) must achieve 5 MPa within 6 weeks of placement. However, no lower time limit is imposed and this enables the contractor to proceed with base paving as soon as the required 5 MPa is achieved.

Curing and debonding of the subbase, where necessary, is an important feature of Australian concrete pavement practice. Sprayed compounds are specified for subbase curing. They may be compounds of wax emulsion (except under continuously reinforced concrete), chlorinated rubber or hydrocarbon resins. Additionally, a second bond breaking interlayer is placed prior to the placement of jointed bases. In contrast, positive debonding is avoided under continuously reinforced pavements because of its undesirable effect on crack spacing and width.

Under jointed pavements, particularly plain concrete bases, the influence of the interlayer has been found to be critical. Too low a friction results in uneven initiation of cracks at transverse sawcuts whilst too high a friction leads to reflection of both cracks and joints from the subbase into the base.

The best interlayer treatments have proven to be either sprayed bituminous seals or a supplementary application of wax emulsion curing compound. The latter has been found to provide the optimum interlayer friction but has the disadvantage of not adequately preventing reflection cracking from more severe subbase cracks and joints.

With this treatment, it is occasionally necessary to "bandage" wider cracks and joints with a material such as bitumen coated geotextile prior to the placement of base concrete.

Sprayed bitumen seals have proven very effective in preventing reflection cracking but at times they are too effective in debonding when applied to surfaces which have earlier been cured with wax emulsions. On some projects, early crack initiation has occurred at between 1 in 3 and 1 in 8 joints and these are obviously of large magnitude. The bitumen is typically applied at a rate of 1.0 l/sq m with a covering of 5 mm aggregate, but trials are currently being monitored to assess the influence of reducing the bitumen application rate to 0.6 l/sq m.

The success rate of the debonding treatment also appears to be influenced by both ambient temperatures and the day/night temperature differential, with success generally being better in milder climates.

Under continuously reinforced concrete pavements (CRCP) positive debonding is avoided because a higher friction is required to induce cracking within the desired spacing range. Best results have been obtained by providing a smooth surface finish on the subbase (such as that provided by the slipformer) followed by the application of chlorinated rubber curing compound. No supplementary debonding treatment is provided. In practice, much of the compound is lost during construction activities such as steel placement but this has no apparent detrimental effects.

BASE

Four formats of rigid pavement have been constructed in Australia; plain concrete, continuously reinforced, dowelled reinforced, and steel fiber reinforced. Each is discussed below.

Plain Concrete Pavement (PCP)

PCP constitutes approximately 80% of the total concrete pavement constructed since 1975.

Key features of the PCP format as constructed in Australia are as follows:

- Lean concrete subbase across the full carriageway including shoulders.
- Undowelled contraction joints at 4.2 m spacing and a skew of 1 in 10.
- Concrete shoulders, either tied or integral, and at the same thickness as the concrete base.
- A pavement anchor at every discontinuity, such as bridge abutments. Additional anchors are sometimes provided on long grades in excess of 4%, to prevent downhill creep.
- Specified concrete shrinkage limit of 450 μ
- Longitudinal joints at spacings of about 4m (to a maximum of 4.6 m). All longitudinal joints are tied in pavement widths up to about 16 m.
- Transverse joints sealed, typically with silicone.

Until 1991, transverse contraction joints were typically placed in accordance with the Californian practice of randomised spacings between 3.7 and 4.6 m, and with a skew of 1 in 6 (80^0). However, a recent review has resulted in changes to both spacing and skew.

The skew has been reduced to 1 in 10 (84^0) because of the occasional incidence of corner cracking in the acute corners. The risk associated with acute slab corners is confirmed by calculation of the induced stresses (7). The skew is usually deleted in low speed areas in view of the reduced impact loading on the joint.

Joint spacing has been modified to a constant 4.2 m to reduce the complexity of construction and the associated risk of construction related failures. This aspect remains under close scrutiny to detect possible resonant effects on ride quality.

The maximum desirable spacing of contraction joints is governed by two factors; viz load transfer and slab integrity.

In terms of load transfer (and in the absence of dowels), the critical factor is to limit the magnitude of joint opening. This dictates that the mean length of adjacent slabs should not exceed about 4·2 m for the combination of temperature range and concrete shrinkage encountered under Australian conditions. Dowels would be provided in slabs exceeding this length.

In terms of *slab integrity*, the critical factor is the slab length (and ratio of length to width) which will be structurally stable both in the freshly placed slab (under the stresses of early contraction and curling) and in the longer term (under the additional stresses of live loading).

The overseas trend towards the increasing use of dowelled plain pavements (PCP-D) is being keenly monitored in Australia, but there remains a prevailing reluctance to follow this lead because of the difficulties and risks associated with their use, particularly those associated with poor alignment. Additionally, axle load limits in Australia are lower (at 8.5t) than those in many overseas countries and the warrant for their use would therefore appear to be substantially reduced, particularly when considered in the light of the overall design of the pavement cross-section.

Two factors could change the current trend; the refinement of the "second generation" automated dowel inserter, and recognition in the 1991 AUSTROADS Thickness Design Method that dowels reduce pavement stresses and hence warrant a significant reduction in thickness relative to undowelled bases.

Continuously Reinforced Concrete Pavement (CRCP)

The CRCP constitutes about 20% of the total rigid pavement constructed in Australia since 1975. Typical applications have been as follows:

* Over very poor subgrade conditions such as coastal flood plains.
* On urban freeways where a high reliability factor is warranted.
* On urban freeways through residential areas where the noise from sawcutting may be unacceptable.
* Through areas of expected significant differential settlement such as mine subsidence areas.

The CRCP exhibits the following substantial benefits over the other formats:

* In the absence of transverse joints it offers potentially the lowest maintenance demand of all pavements.

* It behaves as a relatively flexible "reinforced ribbon" in the longitudinal direction and is therefore ideally suited to areas of potential differential settlement.

* Of all rigid formats it is the most compatible with asphalt wearing courses (where they may be required) because of the minimal movement at the transverse cracks.

Consistent with world-wide trends, increasing pressure is being imposed on Australian road authorities to provide low noise surfaces, particularly within residential areas. Under these conditions, it has been recognised that the combination of a CRCP with an open-grade asphalt wearing surface provides arguably the optimal combination of low maintenance and low noise.

Again consistent with overseas experience, the performance of the CRCP has been found to be directly related to the standard of original construction. Of prime importance are factors such as the positioning and integrity of reinforcement, and the uniformity, strength and compaction of concrete.

Where these criteria have been met, the pavement has performed with zero or minimal maintenance demand. Unfortunately, some projects have not met this standard. By far the most common initiator of failure has been inadequate compaction, but concrete segregation has also contributed to failure in isolated areas.

The Authority's first CRCP was constructed in 1975 on the Pacific Highway near Kempsey (8). The highway had to be constructed at the existing level to allow the passage of water across the flood plain at that location. For most of its length of 5.5 km there is less than 500mm of gravel over the underlying saturated silts.

The pavement continues to perform excellently after 17 years without a single dollar having been spent on its maintenance. The success of this project, in terms of both construction efficiency and final quality, played a large part in boosting confidence within the RTA in the potential of concrete pavements. This particular project was instrumental in prompting the committment to further concrete paving.

Unfortunately, the shoulders on this project were constructed of sealed gravel for economic reasons and their maintenance demand has been quite high at the concrete interface.

This project was constructed using manual placement with fixed forms and by inexperienced RTA crews. In contrast, an adjoining section which was constructed in 1984 by an experienced contractor has required maintenance because of segregation and inadequate concrete compaction.

Jointed Reinforced Concrete Pavement (JRCP)

The JRCP constitutes only a very small proportion of the "new" rigid pavement in Australia but its use continues to be promoted for the following applications:

* In areas of high commercial vehicle volumes, eg industrial areas.
* Where low output, piece-meal construction is unavoidable, such as through busy commercial centres.
* In areas of potentially significant differential settlement.
* Where a subbase other than LCS is to be provided.
* In construction of widened kerbside lanes to match the joint patterns in existing JRC pavements.

This is the most traditional of all formats, and older examples can be seen on many arterial routes throughout Australian cities.

Most of the older JRC pavements have performed very well over long periods, and distress has invariably been initiated by deterioration of erodible subgrades or subbases at transverse joints. Such distress has normally been accelerated by the ingress of water following the deterioration of earlier generation sealants.

Too often, asphalt surfacings have been placed over such pavements with inadequate attention to correcting the inherent failure mechanism and it is not surprising that these surfacings have rarely provided satisfactory long-term performance.

The modern JRCP in Australia will normally be limited in slab length to less than 12 m for structural and economic reasons. One of the benefits is that this reduces the magnitude of joint movement which, in turn, allows a reduction in actual joint groove width to about 10-12 mm. This is important in terms of ride quality because joint grooves will not normally be apparent to drivers at widths less than about 14 mm.

The JRCP is suited to projects which are to employ manual placement methods, and particularly where traffic requirements dictate piecemeal construction. The incorporation of reinforcement also provides a form of insurance in the event of unplanned cracking.

The JRCP is unsuited to slipform paving because the discrete sheets of reinforcing mesh are likely to move under the paver's shoving action.

Steel Fibre Reinforced Concrete Pavements (SFRC)

This format has found application throughout New South Wales in situations such as roundabouts and intersections where high centrifugal loadings place extreme stresses on flexible pavements.

Further, conventional concrete in this application is susceptible to unplanned cracking because of the unavoidably high incidence of odd-shaped slabs. Conventional reinforcement is of little benefit in slab corners of less than about 80^0 whereas SFRC has proven resilient in angles as low as 60^0. Notwithstanding, a desirable minimum angle would appear to be about 70^0, but even this value allows substantial licence in the design of joint layouts.

Local confidence in this product has been boosted by its successful use on heavily trafficked routes in Europe and in particular Belgium (9). It is expected that the SFRC format will gain increasing acceptance for specialist applications in Australia.

PAVEMENT EDGE DRAINS

Experience in New South Wales has demonstrated the importance of effective pavement drainage on the performance of the concrete pavement and it is now policy to provide them on the lower edge of the crossfall. Observations to date indicate that the lean-mix concrete subbase forms an effective waterproofing layer over the embankment and that water which enters (from whatever source) can be efficiently removed by collection at the base/subbase interface on the low side.

The current policy on subsurface pavement drainage is summarised as follows:

* The ingress of both moisture and incompressibles is minimised by specifying the use of silicone joint sealants.

* Edge drains are provided to quickly remove water which does enter the pavement (from whatever source) in order to minimise the potential for subbase and subgrade damage.

High speed commercial vehicles impart extremely high pressures/velocities on water which ponds at the base/subbase interface. This "hydro-jetting" can result in erosion of the subbase surface and expulsion of seals. Pavement edge drains must therefore be designed to provide rapid and lasting drainage conditions.

CONSTRUCTION SPECIFICATIONS

There have been several significant technical developments over the past 10 years which have contributed to an overall improvement in industry and product standards. Significant aspects of current specifications are treated below.

Waste product utilisation

As already noted, the majority of the Australia's concrete pavement since 1975 has incorporated a lean-mix concrete subbase in which typically 60-70% of the cementitious content is flyash. More recently, flyash contents up to 50 kg/m^3 have also been permitted in the base layer. This limit is imposed because of the risk of plastic shrinkage cracking at higher contents.

Slag aggregates have been used in the subbase on several projects, but they do not comply with the current specification for base concrete because of their marginal wet crushing strength.

Curing compounds

The RTA's specification for sprayed curing compounds is justifiably strict in requiring the use of high quality products. Local specifications require at least 90% water retention under testing regimes similar to those specified by ASTM C309.

Until recently, the only satisfactory compounds for use on base concrete have been chlorinated rubber products. However, they contain a high content of xylene and are therefore undesirable both to site staff and from an environmental point of view.

A significant recent development has been the refinement of hydrocarbon resin compounds which meet the specified criteria and they now seem likely to become a popular replacement for chlorinated rubber because of their low toxicity.

Compaction

Australian specifications since the early 1980's have specified compaction standards in the work. The measured degree of compaction is computed by comparing the density of cores taken from the hardened concrete with that from test cylinders moulded from the same concrete.

It is understood that both Switzerland and Georgia (USA) have similar requirements. The apparent disinterest elsewhere in this topic is puzzling when considered in the light of substantial evidence, both research and empirical, which shows the severe impact of under-compaction on strength and hence pavement life.

The coring process is somewhat destructive of the pavement and the potential exists for the use of the nuclear density meter as a non-destructive method in unreinforced concrete. Following encouraging R&D results since 1989, its use is now required in selected contracts on a trial basis but the results are being used for research purposes only and are not used at this stage as acceptance/rejection criteria.

Acceptance criteria for CRCP

The design of continuously reinforced concrete pavements (CRCP) involves a sensitive balance between the thickness and strength of the concrete and the reinforcement ratio. Australian designs are typically as follows:

Concrete:	32 - 42 MPa strength, 210 mm thick
Reinforcement:	0.67%, typically 16 mm deformed bar at 140 mm $^c/c$.

Specifications worldwide have traditionally based their acceptance/rejection criteria on strength alone. A recent development in Australian specifications is the development of acceptance/rejection/penalty criteria based on combined thickness and strength in the completed pavement.

Penalties for non-conformance are directly related to the calculated life reduction. This specification demands very strict control of all paving operations but the acceptance criteria reflect both the design process and the consequences to the client of non-conformance in terms of reduced pavement life. It would seem logical that a contractor with doubts about his capacity to meet the specification would allow an amount in the tender price for an estimated level of penalty.

Performance specifications

Over the past 4 years there has been a concerted effort to replace wherever possible "methods" specification criteria with "performance" based criteria. Success in this regard has probably not been as comprehensive as the legal community would like, but this is due largely to the enormity of the task with products such as cement and concrete.

Aggregate gradings

Combined aggregate gradings are now specified for mixes proposed for slipform placement. The new specification makes conformance testing slightly more difficult, but its introduction was considered warranted because of ongoing problems in some areas caused by contractors' insistence on using only locally available fine aggregates when, for satisfactory results, it was necessary to import supplementary fine sands.

TECHNICAL ISSUES

Experience to date within Australia has consistently shown that the early to medium-term performance of concrete pavements is largely governed by two factors:

* the standard of design detailing, and
* the standard of construction.

Extensive surveys in New South Wales (14) indicate that failure typically occurs in about 0.3% of the pavement within 3 years of construction, but this rate varies markedly on different projects. This figure is clearly too high and is associated directly with the above design and construction deficiencies. The failure rate thereafter becomes insignificant until such time as flexural fatigue failure commences.

Also of influence on the performance of a pavement, whether rigid or flexible, is the influence of external factors such as embankment stability.

Design Detailing

Consistent with experience in most fields of structural engineering, detailed design is critical to the successful performance of a concrete pavement.

The most common sources of early distress in this regard have been:

* mismatched joints.
* excessive or odd-shaped slab dimensions.
* misaligned dowels
* incorrectly placed fittings at moving joints. Some of the early designs for dowel support assemblies effectively locked the joint.

It is critical within the early days after placement that the pavement not be subjected to these significant stresses. Design related failures are often initiated on the night of placement whilst the tensile capacity of the concrete is minimal.

It is important to note that the above distress mechanisms will occur independent of pavement thickness, and therefore an increase in thickness will not increase the safety factor.

The design of joint layouts is most difficult at irregular geometric layouts such as intersections, roundabouts and ramp junctions. When preparing contract documents, it is rarely feasible to prepare "typical" designs to cater for all such situations on a project and it will usually be safer and more efficient to provide site-specific layout designs.

Few motorists on Australia's east coast would not be aware of our most publicised concrete pavement, that on the F3 Freeway about 80 km north of Sydney on the Wyong Bypass. On this section, a longitudinal crack runs for the full length of the truck lane over 7 km of divided carriageway. This resulted from the improper functioning of a ribbon joint inducer at the shoulder/truck lane joint, in combination with the influence of a longitudinal subbase construction joint located under the base crack. It was subsequently learnt that at least one other overseas authority had experienced a similar problem. This experience has resulted in comprehensive ongoing reviews of the RTA's design details.

The Wyong crack has been tied using diagonal cross-stitching as developed by the Utah Department of Transportation, and its surface has been routed and sealed. The repairs continue to perform well after 5 years under very heavy traffic.

Construction Standards

A high proportion of distress in concrete pavements can be attributed to the neglect of old-fashioned principles of good concrete technology; specifically, aspects such as:

* sensible mix design
* mixing uniformity
* appropriate handling and placement techniques
* thorough compaction
* timely and thorough curing

Each of the above topics is treated at depth in any respectable reference manual on concrete technology. Unfortunately, these well established principles are too frequently subjugated by neglect and/or haste under the stresses of job-site activity. However, there should be no doubting that high standards of construction are achievable, even under the frequently severe exposure conditions of highway construction.

A brief discussion is provided below of selected aspects of concrete production and placement as practiced in Australia. Several have been the cause of major contractual disputes, both in Australia and overseas.

Mixing Uniformity

Thorough concrete mixing is essential for the achievement of the design properties of the mix. It is a critical aspect of slipforming because high quality paving demands the supply of uniform concrete at high outputs. Mixing times of 80-90 secs will usually be required for mixers (and mixes) of the type typically used on paving projects.

On a recent New South Wales project, the combined effects of unusually high admixture doses and short mixing times (55 secs) resulted in extreme concrete variability. In some areas, cores less than 1 metre apart gave strengths as disparate as 8 MPa and 45 MPa.

Admixtures

Admixtures play an important part in mix design for slipform paving, particularly under the severe summer conditions encountered over much of New South Wales. However, their use demands close control of every aspect of their selection and incorporation. It will often be found, for example, that two admixtures such as air entrainers and water reducers will form an insoluble gel if inter-mixed in their concentrated form. For this reason, they should be pre-diluted and incorporated by methods which prevent their adverse interaction.

Placing Techniques

The placement of concrete in pavements demands the highest standards of technique and workmanship. The finished work must be well compacted and cured, and close surface tolerances will be required to achieve a satisfactory ride quality.

In fixed form work, it is necessary to use internal vibration followed by two passes of a vibrating screed. For maximum benefit, it is critical that the screeds be used correctly. In contrast, non-vibratory screeding provides only minimal compaction and is unlikely to fill voids left in the mix by the workers' boots.

With the use of sophisticated equipment such as slipform pavers it is all too easy to overlook the old-fashioned fundamental rules of concrete placement. Such machinery has the **capacity** to produce high quality work but such quality will only be achieved if all of the basic rules of concrete placement are observed. Adequate pre-spreading, correct use of the spreader augers, and controlled paver speed are essential.

It is also essential that the machine be operated in harmony with the characteristics of the mix. This appears to be most critical with smaller, single lane pavers.

Compaction

The effect of under-compaction on concrete strength is dramatic. However, under-compaction will rarely occur if the correct paving techniques are used with a good concrete mix. Paver travel speed is critical, and Australian experience shows that a speed of about 1 m/min will generally provide optimum results. Speeds in excess of about 1.5 m/min have rarely been satisfactory.

Transverse construction joints are a regular source of difficulty through under-compaction. Few pavers will adequately compact concrete against a previous pour and thorough hand compaction is therefore required in that area.

Surveys world-wide have shown that under-compaction is a far more common problem than is over-vibration. Recommended vibrating times are much longer, and insertion spacings much closer than those typically used in the industry.

Finishing

Finishing and curing techniques must be of the highest standard to ensure the achievement of a surface texture which is durable under the highly abrasive action of highway traffic. Durability is related to concrete strength which, in turn, is largely influenced by water/cement ratio and effectiveness of curing.

In this regard, the two most common abuses of concrete involve the use of over-wet mixes and wet slurrying of the surface, both intended to aid the finishing operation. These practices result in a surface mortar of high water/cement ratio and hence low strength. Sprayed evaporation retarders are often also incorrectly used as surface finishing aids.

Curing

The effect of curing on the strength of concrete is dramatic. Less well known is the equally dramatic influence that poor curing has on the permeability of the mix and hence its durability. For example, a mix with water/cement (w/c) ratio of 0.45 requires 7 days of full curing to produce a discontinuous system of capillaries. A mix with w/c ratio of 0.50 requires 28 days, and one of 0.60 requires 180 days.

Australian summer conditions are relatively severe and mandate the adoption of very good curing practices. Australian specifications justifiably require high quality curing compounds and a high standard of application to maximise the durability of the surface texture.

Embankment Construction

Of major influence on the long-term serviceability of the pavement is the integrity of the underlying embankment.

There is ample evidence to show that rigid pavements can perform very well over extremely poor subgrade conditions, but the critical factor is the uniformity of support, in terms of both area and time.

Basic to this point is the fact that all thickness design methods assume the provision of reasonably uniform subgrade conditions, though the means of specifying such "uniformity" is a highly subjective issue.

There are three main considerations in this regard.

The first is the choice of a figure for subgrade strength to input to the thickness design formulae. This is by no means a simple process, but its discussion is beyond the intended scope of this paper.

The other two aspects involve the adequacy of the embankment in terms of:

- its potential for differential consolidation, a condition which would compromise ride quality.
- in extreme cases of differential settlement, the pavement can suffer structural damage.

Reinforcement in jointed pavements, where provided, is intended merely for crack containment and is not located in the flexural tensile zone.

Special attention is required during construction at the approaches to structures, in the reinstatement of trenches, at cut-fill transitions, and in areas of mine subsidence and expansive soils.

Bridge Approach Slabs

Approach slabs are provided at all structures in order to minimise the effects of embankment consolidation. The slab typically has a span of 3 m, but this may be increased where the severity or consequences of settlement are likely to be significant.

Concrete Shoulders

The structural and operational benefits of concrete shoulders have long been recognised worldwide. Australian road authorities adopted their use in 1981 and a comparison of the performance of local concrete shoulders with earlier flexible shoulders provides ready evidence of their value. These findings would seem to be strongly supported by the findings of both overseas field experience and recent design models (15).

The AUSTROADS Pavement Thickness Design Method (1991) reflects recent overseas design refinements which allow a reduction in the pavement thickness in conjunction with the incorporation of tied or integrally paved concrete shoulders.

Pavement Anchors

Pavement anchors are specified by the RTA at the termination of rigid pavements, for the following reasons:

* To maintain transverse joints at design widths. This is critical for shear transfer at undowelled joints, but in all joints it prevents the ingress of detritus which will ultimately lead to "growth" of the pavement with cyclic temperature changes.

* To restrain growth in the concrete pavement and hence protect adjoining structures and flexible pavements from damage. Special attention is given to the anchor design where grades in excess of 4% approach a structure.

Anchors are used worldwide in continuously reinforced pavements, but their use in jointed pavements appears to be rare. In their absence, it is very common to see pavement "blowups" and structural damage to bridges.

Accelerated Acceptance Testing

In view of the substantial daily quantities of concrete routinely placed in slipform paving operations, the need is recognised to refine an accelerated acceptance procedure for concrete. Various methods have been used successfully overseas on large civil projects, but few highway authorities have adopted such procedures. Two known exceptions are Spain and Georgia (USA). The RTA is currently researching and trialling those methods which would seem most applicable to Australian conditions.

Documentation and Training

In 1984 the RTA compiled a Design and Construction Manual as a reference source for designers and supervisors. Substantial reviews since that time reflect the major technical development which resulted from experience throughout the 1980s. To our knowledge, it is one of the few manuals of its type in the world and is used by road authorities throughout Australia and South East Asia.

A companion Concrete Pavement Maintenance Manual is currently under preparation.

In conjunction with the release of the first manual the RTA undertook a comprehensive training program for staff and consultants. This proved to be a substantial task because of rapid expansion in the industry and because of the ongoing turnover of construction personnel within the road authorities. The program continues to operate under constant demand from the field and is considered to form a vital part of the ongoing development of industry standards.

Australasian Concrete Pavement Association

In March 1992, at the initiative of the Cement and Concrete Association, the inaugural meeting was held of the Australasian Concrete Pavement Association (ACPAVE). The group comprises representatives of the CCAA, paving contractors, materials suppliers and road authorities.

ACPAVE's early activity has been very enthusiastic and there seems little doubt that it forms the basis for an organisation which will follow the example set by groups such as the American Concrete Paving Association and Britpave in advancing the industry and its standards through co-operative communication.

A future priority will be to promote participation from the South East Asian region, as evidenced by the adoption of the title "Australasian".

SURFACE TREATMENTS

The issue of traffic generated noise has become a topic of significant public interest in Australia since 1989 and consequently, pavement surfacings are being more critically assessed than ever before.

This issue creates a substantial challenge for highway engineers in their search for a surfacing which is quiet and durable, with high friction characteristics. There is no single solution to the problem because the optimal surfacing will change according to factors such as:

* the predominant traffic speed
* the commercial vehicle content
* the continuity of traffic flow.

The quietest surfacing used in Australia is permeable asphalt and for that reason it must surely rate as the most popular with the general public.

However, from an engineering sense, a concrete surface provides the optimal solution in terms of skid resistance, durability and (arguably) economics.

The life of permeable asphalt is generally less than 10 years and its use as a surfacing over concrete therefore adds substantially to the total life cycle costs of the pavement. Additionally, an asphalt surfacing provides no structural contribution to the rigid pavement and may even detract from its long-term performance by encouraging the postponement of desirable routine maintenance (such as sealant replacement) on the underlying concrete.

Encouraged by public opinion, considerable work has been devoted to the refinement of concrete surface treatments during the past 3 years in Australia and the results achieved thus far have been rewarding.

Techniques pursued to date have generally been consistent with the recommendations of Descornet (12) and Fuchs (13). Various combinations of longitudinal hessian drag and transverse tining have been trialled and the results are reported by Nichols and Dash in these conference proceedings.(10)

The most successful has been a combination of light hessian (burlap) drag (longitudinally) and light transverse tining. The subjective assessment of the new surfacing by construction personnel is most favourable and this is endorsed by the limited public response available to date.

In all pavement concrete, Australian specifications require that at least 40% by mass of total aggregate content be quartz sand, this to ensure adequate microtexture for skid resistance purposes.

For areas with speeds of less than 80 km/h, specifications typically require a medium hessian drag finish, without tining. For these speeds, this surface exhibits low noise generation and high skid resistance and is superior to dense grade asphalt on both accounts.

Permeable asphalt will not normally be used in Australia in urban areas with discontinuous traffic flow because of its degradation under fuel and oil droppings.

THE PURSUIT OF QUALITY

High output paving is technically demanding and is sensitive to standards in materials and workmanship. Good quality control of the process is therefore critical. Australia's experience shows that end product control alone is inadequate.

To this end, the Australian Federal Department of Transport (DOT) undertook a committment in 1988 to the development of Quality Assurance (QA) management for major public contracts. The first QA highway contract was awarded in 1989 and it is now used on all contract works on National Highways.

The application of QA management extends even as far as having contractors conduct their own acceptance testing, a concept which would have been anathema to most construction agencies until just a few years ago. Refinement of the QA processes has been demanding of all contract managers, and much work remains to be done.

REFLECTIONS ON THE 80s

Industry Performance

The RTA's construction of concrete pavements increased significantly from the late 1970's and witnessed two peaks; the first within the period 1983-88 under the momentum of the Australian Bicentennial Road Development (ABRD) Program (to coincide with 200 years of European settlement in Australia) and the second in 1992/93. During these periods the RTA has been one of the biggest single users of cement in Australia.

These were periods of rapid evolution of expertise on the part of both the RTA and the contracting industry. Also relevant was the fact that some uncertainty existed regarding the likely future of the industry at the end of the ABRD program. These fears proved to be well founded because paving activity waned in the period 1988 to 1991. However, by late 1991 several major projects had commenced and the existing construction resources will be significantly stretched until at least late 1993.

It is often claimed in the industry that major slipform paving necessarily involves a long "learning curve". However, it can be readily demonstrated that competent paving teams have been able to achieve optimum performance with high outputs within days of their first attempts.

A notable change in Australian policy over the past 5 years has been the trend towards "specialist" contracts such as those purely for pavements, in lieu of the previous practice of awarding all encompassing contracts for earthworks, bridges and pavements. This change appears to have removed the pressure on contractors to recoup losses on one activity by maximising profits on another.

It was of great interest to Australian highway engineers to read the comments of Mr Wayne Muri, of the Missouri Transportation Department (16) in reporting that European highways are better than those in the USA, despite the fact that trucks are heavier and volumes are higher.

Mr Muri attributes this to the following factors:

* that Europeans invest far more in their highways and that they have better technology which is implemented more rapidly, and

* that the European emphasis is on quality and effectiveness, rather than efficiency.

He considers the latter point to be an important consideration when we are entering " ... *an era of brutal economic competition in the marketplace*."

Recent achievements within Australia show that the technology and capability exist to construct concrete pavements to world standards. One of the major challenges of the 1990's will be to consistently achieve those standards.

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